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Layout Geometry in Encoding and Retrieval of Spatial Memory

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Two experiments investigated whether the spatial reference directions that are used to specify objects' locations in memory can be solely determined by layout geometry. Participants studied a layout of objects from a single viewpoint while their eye movements were recorded. Subsequently, participants used memory to make judgments of relative direction (e.g., "Imagine you are standing at *X*, facing *Y*, please point to *Z*"). When the layout had a symmetric axis that was different from participants' viewing direction, the sequence of eye fixations on objects during learning and the preferred directions in pointing judgments were both determined by the direction of the symmetric axis. These results provide further evidence that interobject spatial relations are represented in memory with intrinsic frames of reference.

Keywords: spatial memory, spatial reference directions, layout geometry, eye movement

As people interact with objects in the surrounding environment, they encode the locations of important objects in memory and retrieve the remembered locations of those objects. In general, encoding develops and refines spatial memory, whereas retrieval uses it. Hence, the behavioral patterns in both encoding and retrieval should be informative about the nature of spatial memory. In this study, we examined the behavioral patterns in both encoding and retrieval of spatial memories to provide converging evidence for the hypothesis that people use intrinsic frames of reference to represent locations of objects.

Mou, McNamara, and their colleagues (McNamara, 2003; Mou & McNamara, 2002; Mou, Zhang, & McNamara, 2004; Shelton & McNamara, 2001; see also Hintzman, O'Dell, & Arndt, 1981; Tversky, 1981; Werner & Long, 2003; Werner & Schindler, 2004; Werner & Schmidt, 1999) have proposed that people use intrinsic reference directions to specify locations of objects in memory. An intrinsic reference system is a type of environmental spatial reference system because it can be defined independently of the observer's location and orientation (Mou & McNamara, 2002) and because its reference directions remain unchanged when the observer locomotes in the environment (Mou, McNamara, Valiquette, & Rump, 2004). In an intrinsic reference system, the locations of objects are specified with respect to reference directions intrinsic to the array of objects. Intrinsic reference directions may be established by layout geometry (e.g., bilateral symmetry), perceptual organization (e.g., rows and columns formed by chairs in a classroom), explicit instructions, or even subjectively salient perceptual properties (e.g., alignment of several objects from a particular viewing direction). Intrinsic reference directions establish privileged directions analogous to the intrinsic orientation of a shape (e.g., Rock, 1973).

Mou and McNamara (2002) hypothesized that when people remember locations of objects, they need to establish a spatial reference system with one or two orthogonal axes in the layout itself (e.g., the rows and columns formed by chairs in a classroom). Mou, McNamara, Valiquette, and Rump (2004) further hypothesized that the angular direction from one object to another might be defined with respect to the intrinsic reference direction selected. With the assumption that retrieval of an interobject spatial relation that is specified with respect to the selected intrinsic reference directions is more efficient than retrieval of a spatial relation that is not specified with respect to the selected intrinsic reference directions (e.g., Klatzky, 1998), Mou et al.'s hypothesis predicts that judgments of relative direction (e.g., "Imagine you are standing at the battery, facing the apple; point to the lock") should be easier for imagined headings parallel to the intrinsic reference directions than for imagined headings not parallel to the intrinsic reference directions selected.

One alternative spatial reference system that people may establish in memory is an egocentric reference system (Diwadkar & McNamara, 1997; Shelton & McNamara, 1997; Simons & Wang, 1998; Wang & Simons, 1999). In such a reference system, loca-

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tions of objects are represented with respect to the body axes of the observer. This hypothesis has been supported by findings that judgments of relative direction were viewpoint dependent (e.g., Shelton & McNamara, 1997). However, Shelton and McNamara (2001) reported findings that are difficult to explain if one assumes that long-term spatial memories are encoded with respect to egocentric reference systems. In one of their experiments, participants learned a layout of objects from two viewpoints, one aligned and the other misaligned with salient frames of reference in the environment (e.g., edges of the mat on which objects were placed and the walls of the surrounding room). Participants then made judgments of relative direction, using their memories. The pointing judgments were better at the imagined heading parallel to the aligned learning viewpoint than at novel imagined headings, but the pointing judgments parallel to the misaligned learning viewpoint were not better than at novel imagined headings. This pattern of results is challenging to explain in an egocentric representation model because such models predict good performance for experienced views.

Mou and McNamara (2002) provided compelling evidence that the spatial reference direction in memory is intrinsic rather than egocentric. In Experiment 3 of their study, participants learned locations of seven objects on the floor of a cylindrical room. Participants were instructed to learn the layout of the objects along an intrinsic axis (direction of 0°) that was different from their viewing perspective (direction of 315°). After learning, participants made judgments of relative direction, using their memories. Pointing judgments were more accurate for imagined headings parallel to the direction of 0° than for other imagined headings, including the direction of 315°, which was the viewing direction. Also, pointing judgments were more accurate from the novel imagined headings of 90°, 180°, and 270°, which were aligned with (i.e., parallel or orthogonal to) the instructed direction of 0°, than from the novel imagined headings of 45°, 135°, and 225°, which were aligned with the viewing direction of 315°, producing a sawtooth pattern across imagined headings. The intrinsic-orientation dependent pattern and the sawtooth pattern suggested that participants established an intrinsic frame of reference with two orthogonal axes (0°–180° and 90°–270°) to specify locations of objects in memory.

In a recent study, Mou, Zhao, and McNamara (2007) provided additional evidence that spatial reference directions in memory are intrinsic. They showed that a geometric property of the layout of objects (viz., bilateral symmetry) had an influence in determining the preferred directions in judgments of relative direction. Participants learned the layout of seven objects on the floor of a cylindrical room from three viewpoints (0°, 90°, and 225°), among which the viewpoint of 225° was parallel to the symmetric axis of the layout. Then participants moved to a different room and used their memories to make judgments of relative direction. Pointing judgments were better for the imagined headings of 45°, 135°, 225°, and 315°, which were aligned with the symmetric axis of the layout, than for the imagined headings of 0°, 90°, 180°, and 270°, which were not aligned with the symmetric axis of the layout. There was no evidence that the viewing directions of 0° and 90° were preferred in judgments of relative direction.

However, these two studies (Mou & McNamara, 2002; Mou et al., 2007) did not show that people are able to select intrinsic reference directions different from the viewing direction solely under the influence of the layout geometry. In Mou and McNamara's (2002) experiments, participants were instructed to learn the locations of the objects along an axis that differed from their viewing direction. In Mou et al.'s (2007) experiments, the symmetric axis of the layout was parallel to one of the viewing directions. The better performance at the imagined headings aligned with the symmetric axis may have been the conjunctive effect of both the layout geometry and the viewing direction.

The aim of the present study was to determine whether people are able to select intrinsic reference directions different from their viewing direction solely under the influence of the layout geometry. In Experiment 1, participants learned a layout of seven objects with a symmetric axis from a single viewing direction. The symmetric axis of the layout was different from the viewing direction. The purpose of this experiment was to test whether the viewing direction or the symmetric axis would determine the spatial reference directions in memory. In Experiment 2, two objects were added to the layout used in Experiment 1 to remove the symmetric axis of the layout. The purpose of this experiment was to determine whether this manipulation could alter the spatial reference directions selected by participants. If the spatial reference directions were determined by the symmetric axis in Experiment 1 and were altered when the symmetric axis was removed in Experiment 2, it would suggest that the spatial reference directions can be solely determined by the symmetric axis of the layout and, hence, that locations of objects are mentally represented with respect to intrinsic frames of reference. We expected that the spatial reference directions were determined by the learning direction of the participant in Experiment 2 because the learning direction can determine the directions of spatial reference systems (e.g., Shelton & McNamara, 2001).

In the spatial memory literature, the patterns of performance in spatial memory retrieval (e.g., judgments of relative direction, scene recognition) have commonly been used to infer the nature of spatial memory. To our knowledge, no study so far has used the pattern of encoding of spatial memory to infer the directions of the spatial frames of reference. In this study, we recorded participants' eye movements when they were learning the locations of objects and collected their responses in judgments of relative direction when their memory was tested. Our goal was to examine whether the viewing direction or the symmetric axis of the layout would determine the preferred directions of eye movements during encoding of spatial memory as well as the preferred directions in judgments of relative direction during retrieval of spatial memory.

We identified two reasons why the preferred directions of eye movements during learning might be sensitive to the spatial reference systems used to represent locations of objects. First, eye movements may be involved in the selection of spatial reference directions. Eye movements may be a measure of attention to those spatial aspects of the scene that end up being used as an intrinsic reference system. People look at what they pay attention to, and they pay attention to aspects of the scene that are used to form a reference system. A second reason that eye movements may be sensitive to spatial reference systems is that they may be involved in encoding interobject spatial relations. Rump and McNamara (2006) provided evidence that interobject spatial relations aligned with spatial reference directions are represented with greater probability or fidelity than are other spatial relations. Eye movements may be a measure of the cognitive processes involved in encoding such spatial relations. These two explanations are not mutually exclusive. An additional process that may be functional under either of these explanations is that programming eye movements may be more efficient when the direction from one object to another is aligned with a spatial reference direction. For two such objects, only the relative distance with respect to one reference direction needs to be specified (e.g., a battery is 21 cm north of a clip), whereas for two objects whose interobject direction is not so aligned, the relative distances with respect to two reference directions may need to be specified (e.g., an apple is 21 cm north and 21 cm east of a clip).[1] In summary, there are several plausible reasons why the preferred directions of eye movements may be sensitive to the spatial reference directions in memory.

By examining the preferred directions in both encoding and retrieval of spatial memory, we sought to obtain converging evidence in determining the spatial reference directions that specify objects' locations in memory.

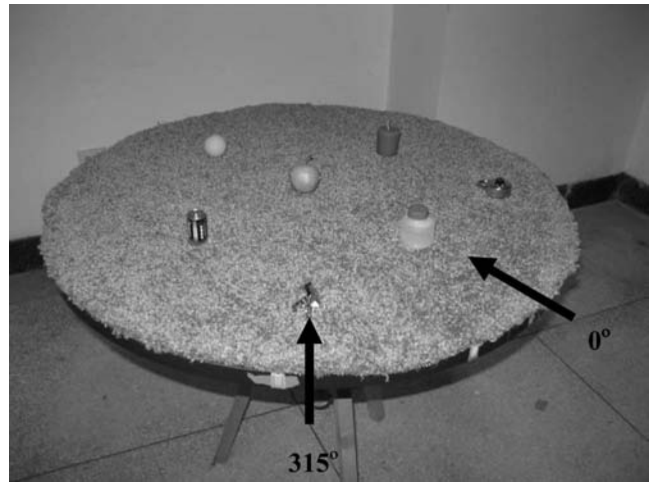

Figure 1. Layout of objects used in Experiment 1.

Experiment 1

In Experiment 1, participants learned the locations of seven objects on a circular table (illustrated in Figure 1) from a single viewpoint that was indicated by the arrow of 315° in the figure (along clip–apple) in a rectangular room. The bilaterally symmetric axis of the layout (along glue–apple–ball) was 45° counterclockwise from the viewing direction and was indicated by the arrow of 0° in the figure. Both the viewing direction and the direction of the symmetric axis were 22.5° misaligned with the wall of the room visible in Figure 1 so that the effect of the room structure should have been equivalent for both the viewing direction and the direction of the symmetric axis. Participants were never instructed to learn the objects' locations along any particular axis. The main purpose of this experiment was to determine whether participants would establish a spatial frame of reference that was aligned with the symmetric axis or the viewing direction, as indicated by eye movements during encoding and judgments of relative direction during retrieval.

Method

Participants

Eight university students (5 men, 3 women) participated in return for monetary compensation.

Material and Design

The layout was presented on a table with a height of 69 cm and a diameter of 80 cm in the lab room (Figure 1). The layout consisted of a configuration of seven objects. Objects were selected with the restrictions that they be visually distinct, fit within approximately 6 cm on each side, and not share any obvious semantic associations. The distances between the clip and the glue and between the clip and the battery were both 21 cm. The distance between the clip and the apple was 30 cm.

The symmetric axis (along glue–apple–ball) was arbitrarily defined as the direction of 0°, and all other allocentric directions were defined counterclockwise accordingly. For example, the viewing direction (along clip–apple) was defined as the direction of 315°, and the direction along lock–apple was defined as the direction of 45°. Both the directions of 0° and 315° were 22.5° misaligned with the wall of the room shown in Figure 1.

An Eye Link II eye tracker (SR Research Limited, Mississauga, Ontario, Canada) was used to track eye movements when participants learned the locations of the objects in the layout. An interobject eye movement was defined as the movement from one fixation on an object to the next fixation on a different object. All interobject eye movements were divided into three categories: (a) eye movements along the aligned-0° axes, which included all eye movements along the directions of 0° (e.g., one fixation on the clip to the next fixation on the battery), 90° (e.g., one fixation on the lock to the next fixation on the glue), 180° (e.g., one fixation on the ball to the next fixation on the apple), and 270° (e.g., one fixation on the clip to the next fixation on the glue), (b) eye movements along the aligned-315° axes, which included all eye movements along the directions of 45° (e.g., one fixation on the lock to the next fixation on the apple), 135° (e.g., one fixation on the candle to the next fixation on the glue), 225° (e.g., one fixation on the battery to the next fixation on the glue), and 315° (e.g., one fixation on the clip to the next fixation on the apple), and (c) eye movements along the other axes, which included all eye movements along all other directions (e.g., one fixation on the clip to the next fixation on the ball). The directions in the category with the highest frequency of the observed interobject eye movement were regarded as the reference directions of the spatial reference system that was established in encoding the objects' location in spatial memory. We did not use measures of eye fixations on individual objects (e.g., duration or frequency) because (a) we could not conceptualize a clear relation between eye fixations on individual objects and the preferred spatial reference direction inside the array of objects and (b) we were concerned that eye fixations on

[1] Reference directions in spatial representations can be conceptualized as cognitive cardinal directions, and it is in this sense that the terms *north* and *east* are used in this example (see Shelton & McNamara, 2001). Cognitive north and east need not bear any relation to their geographical or magnetic counterparts.

individual objects would be influenced by irrelevant object features (e.g., color and size).

Judgments of relative direction were used to infer the preferred directions in retrieving spatial relations from the memory. Each test trial was constructed from the names of three objects in the layout and required participants to point to an object as if standing in a particular position within the layout, for example, “Imagine you are at the glue facing the apple. Point to the candle.” The first two objects established the imagined standing location and facing direction (e.g., glue and apple), and the third object was the target (e.g., candle).

The primary independent variable for judgments of relative direction was imagined heading. Eight equally spaced headings were used. Headings were defined in the same way as the allocentric direction was defined earlier, from 0° to 315° in 45° steps beginning with the position labeled 0° in Figure 1.

Pointing direction (the direction of the target object relative to the imagined heading) was varied systematically by dividing the space into three areas: front (45°–0° and 0°–315°), sides (315°–225° and 135°–45°, not including endpoints of intervals), and back (135°–180° and 180°–225°). We created 48 trials, 6 trials at each of 8 imagined headings. These trials were chosen according to the following rules: (a) three pairs of standing objects and facing objects were used for each heading; (b) two target objects were used in each direction of front, sides, and back; (c) of the six target objects used for each heading, one was pointed to twice; and (d) across all headings, each object was used nearly the same number of times as the standing, facing, and pointing objects, respectively. As a result, the pointing directions were equivalent across the imagined headings. For example, pointing directions at the imagined heading of 0° included 45°, 90°, 135°, 225°, 288°, and 315° clockwise from the imagined heading, whereas pointing directions at the imagined heading of 225° included 45°, 90°, 135°, 225°, 297°, and 315° clockwise from the imagined heading. Participants were given 10 blocks of the 48 trials. The order in which the trials were presented in each block was randomized.

The dependent measures in judgments of relative direction were the response latencies, measured as the latencies from the presentation of the name of the target object to the pointing response, and the angular error of the pointing response, measured as the absolute angular difference between the judged pointing direction and the actual direction of the target. In this experiment and the following experiment, angular error was not as sensitive as pointing latency to the effect of imagined heading, but generally there were no accuracy–latency trade-offs (there was a positive correlation between pointing angular error and pointing latency across imagined headings). Therefore, for brevity the analyses of angular error were not presented in detail. The less sensitivity of pointing angular error to imagined heading may result from some participants’ abilities to compute spatial relations at the imagined headings misaligned with the intrinsic reference direction at the cost of longer latency (e.g., Mou et al., 2007).

Procedure

Learning phase. Before entering the study room, each participant was instructed to learn the locations of the objects for a spatial memory test and was trained in how to use a joystick to make a relative direction judgment. The participant was blindfolded and led to the viewing position that was 35 cm from the edge of the table. The blindfold was removed, and the participant donned the Eyelink II helmet. After calibration of the eye tracker system, the participant was asked to learn the locations of the objects as accurately as possible. The participant viewed the display for 30 s before being asked to name and point to, with eyes closed, the objects in any order they preferred. After five such viewing–pointing sessions, the participant was blindfolded and led by the experimenter to the testing room. All eye fixations were recorded while the participants viewed the display in each viewing–pointing session.

Testing phase. Seated in a chair, the participant wore an earphone and held a joystick. The test trials were presented through the earphone attached to a PC computer. The participant first initiated each trial by pressing a button on the joystick. Trials proceeded as follows: The imagined standing location and facing object were given aurally (e.g., “Imagine you are standing at the glue facing the apple”). The participant was instructed to pull the joystick trigger when he or she had a clear mental image of where he or she was standing and what he or she was facing. The target object was immediately presented aurally when the participant pulled the trigger (e.g., “Point to the candle”). The participant used the joystick to point to where the target would be if he or she occupied the standing location and facing direction as presented. The participant was instructed to hold the joystick exactly in the front of his or her waist and to keep the joystick forward when he or she pointed. Pointing accuracy was emphasized and speedy responses were not encouraged.

Results

Interobject Eye Movements

An example of 1 participant’s eye movements during learning is illustrated in Figure 2. A fixation, with less than 7 cm distance to the center of any object, was regarded as the fixation

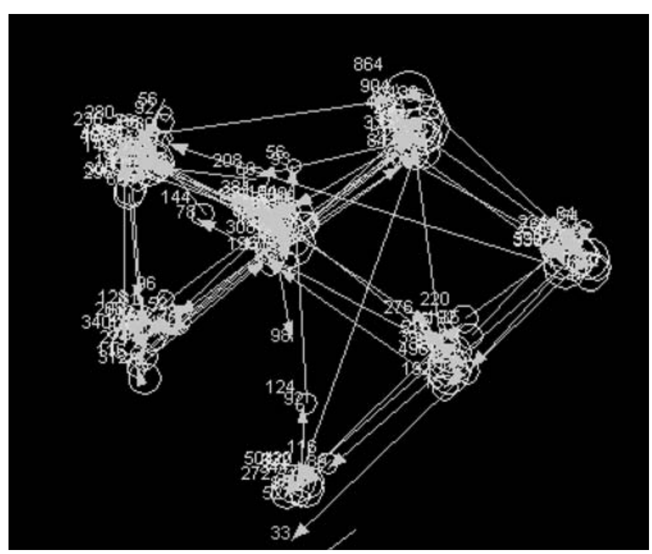

Figure 2. An example of eye movement during learning the layout in Experiment 1.

on that object. The total frequencies of interobject eye movements in the five 30-s viewing periods of the five learning–pointing sessions for each interobject eye movement category and each participant are presented in Table 1. There are 42 possible interobject eye movements (from each of the 7 objects to all of the other 6 objects) distributed as follows across the three categories: 22 for aligned-0°, 12 for aligned-315°, and 8 for other axes. Hence, the a priori proportion of the aligned-0° category in the aligned-0° category and the other category is 73%: 22/(22 + 8). The a priori proportion of the aligned-0° category in the categories aligned-0° and aligned-315° is 65%: 22/(22 + 12). Binomial tests including the category of aligned-0° and the category of other showed that for all participants, the observed proportion of interobject eye movement in the category of aligned-0° was significantly higher than 73%, $\chi^2(1) \geq 27.28$. Binomial tests including the category of aligned-0° and aligned-315° showed that for 6 of the 8 participants (Participants 1, 3, 4, 5, 6, and 8 in Table 1), the observed proportion of interobject eye movement in the category of aligned-0° was significantly higher than 65%, $\chi^2(1) \geq 4.18$. Although the observed proportion of the category aligned-0° was 70% for Participant 2, 68% for Participant 7, and numerically higher than 65%, these values were not significantly different from 65%, $\chi^2(1) \leq 1.71$.

The percentages of interobject eye movements along all directions (0° to 315° in 45° steps and others) for each participant were also calculated. Mean percentage of interobject eye movements is plotted in Figure 3 as a function of direction. The a priori percentage of interobject eye movements is also plotted as a function of direction. As illustrated in Figure 3, the observed percentages along the directions of aligned-0° were higher than predicted by the a priori percentages, whereas the observed percentages along the directions of aligned-315° were not higher or lower than predicted by the a priori percentages. The observed percentage along the directions of other axes was much lower than predicted by the a priori percentage.

The difference between the observed percentage of eye movements and the a priori percentage of eye movements was analyzed in repeated measure analyses of variance (ANOVAs) with terms for direction (0° to 315° in 45° steps). The effect of direction was significant, $F(7, 49) = 8.39$, $p < .001$, $MSE = 0.001$. The percentage difference at the directions of aligned-0° was significantly higher than that at the directions of aligned-315°, $t(49) = 8.36$. More specifically, the planned comparisons showed that the percentage difference at directions parallel to the symmetric axis (0° and 180°) was significantly higher than that at the directions of aligned-315°, $t(49) = 5.23$. The percentage difference at the directions orthogonal to the symmetric axis (90° and 270°) was significantly higher than that at the directions of aligned-315°, $t(49) = 8.42$.

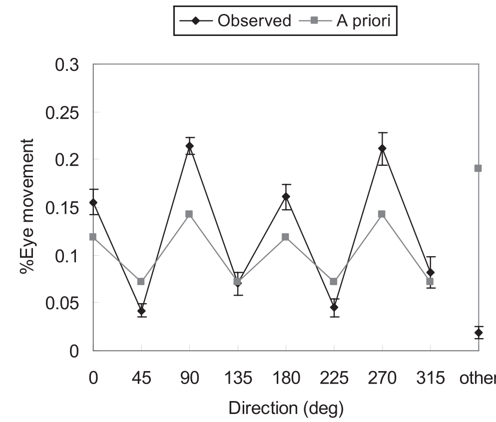

Figure 3. Observed percentage and a priori percentage of interobject eye movements as a function of direction in Experiment 1. Error bars are confidence intervals corresponding to ± 1 *SE*, as estimated from the analysis of variance.

Judgments of Relative Direction

Pointing latency was analyzed in repeated measure ANOVAs with terms for imagined heading (0° to 315° in 45° steps). Mean pointing latency is plotted in Figure 4 as a function of imagined heading. As illustrated in Figure 4, there were two major findings. First, participants were quicker when pointing to objects from the imagined heading of 0°, which corresponded to the symmetric intrinsic axis, than when pointing to objects from the imagined headings of 315°, which corresponded to the viewing direction. Second, participants were quicker when pointing to objects from the imagined headings of 90°, 180°, and 270°, which were aligned

Table 1
The a Priori Frequency of Interobject Directions and the Observed Frequencies of Interobject Eye Movement Along the Aligned-0° Axes, the Aligned-315° axes, and the Other Axes in Experiment 1

Axes	A priori frequency	Observed frequency for each participant (P)							
		P1	P2	P3	P4	P5	P6	P7	P8
Aligned-0°	22	106	100	168	152	162	120	198	146
Aligned-315°	12	30	43	49	32	29	46	95	57
Other	8	1	1	8	1	1	8	11	2
χ^2		10.43**	1.71	15.36**	25.82**	33.83**	4.18*	1.06	4.63*

Note. Chi-square values were calculated from a binomial test comparing the observed frequencies of interobject eye movement along the aligned-0° axes and the aligned-315° axes under a binomial distribution with a probability parameter determined by the a priori frequencies. Aligned-0° axes = directions 0°, 90°, 180°, and 270°; aligned-315° axes = directions 45°, 135°, 225°, and 315°; other axes = all other directions.
** $p < .01$. * $p < .05$.

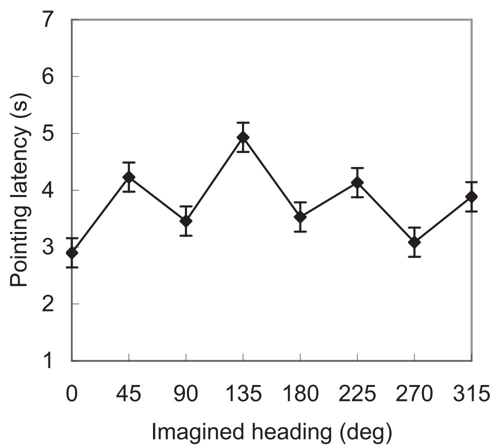

Figure 4. Pointing latency as a function of imagined heading in Experiment 1. Error bars are confidence intervals corresponding to ±1 *SE*, as estimated from the analysis of variance.

with the symmetric axis, than when pointing to objects from the imagined headings of 45°, 135°, and 225°, which were aligned with the viewing direction.

All of these conclusions were supported by statistical analyses. The effect of imagined heading was significant, $F(7, 49) = 6.67$, $p < .001$, $MSE = 0.53$. The planned comparisons showed that latency at the heading of 0° was significantly different from latencies at the headings of 45°, 135°, 225°, and 315°, $t(49) \geq 2.71$, but was not significantly different from latencies at the headings of 90°, 180°, and 270°, $t(49) \leq 1.73$. The planned comparison of the novel headings of 90°, 180°, and 270°, which were aligned with the symmetric axis of 0°, to the novel headings 45°, 135° and 225°, which were aligned with the viewing direction of 315°, was significant, $t(49) = 5.11$.

Mean angular error is presented in Table 2 as a function of imagined heading. Three of the 8 participants pointed quite accurately, with angular error less than 25° for all imagined headings. The accurate pointing across all imagined headings indicated that several participants were able to compute spatial relations accurately at the imagined headings misaligned with the intrinsic reference directions. After five viewing–pointing sessions at the learning phase, some participants might have formed spatial representations of sufficiently high fidelity that accurate spatial relations could be computed from nearly all imagined headings, at the cost of longer latencies (as shown previously). The Pearson *r* between mean latency and mean angular error across headings was .56, which was not significant. The positive correlation between pointing angular error and pointing latency across imagined headings suggests that there were no accuracy–latency trade-offs, which assured the validity of the conclusion based on the findings of pointing latency.

Discussion

The results of interobject eye movements showed that all 8 participants moved their eyes to fixate on the next object more frequently along the directions aligned with the symmetric axis than along the directions aligned with their viewing direction. This preference of the symmetric axis was statistically significant for 6 of the 8 participants. The results of judgments of relative direction showed that retrieval of spatial memory from headings aligned with the symmetric axis was quicker than from headings aligned with the viewing direction. These results lead to two important conclusions: First, people are able to represent in spatial memory the structure of a layout in terms of a spatial frame of reference solely determined by the layout geometry. Second, the same spatial frame of reference is used when people encode spatial memories as when they retrieve spatial memories.

Experiment 2

In Experiment 2, two objects were added to the layout used in Experiment 1 such that it was no longer bilaterally symmetric about the intrinsic axis of 0°–180° (see Figure 5). If participants in Experiment 1 preferred the directions aligned with the intrinsic axis of 0°–180° because it was the symmetric axis of the layout, the preference for directions aligned with the intrinsic axis of 0°–180° would not be observed in this experiment. Instead the directions aligned with the intrinsic axis of 315°–135°, which is parallel to the viewing direction, would be preferred if viewing direction is a strong cue in selection of intrinsic reference direction in the absence of other salient cues (e.g., Shelton & McNamara, 2001).

Method

Participants

Eight university students (4 men, 4 women) participated in return for monetary compensation.

Table 2
Mean (and Standard Deviation) Angular Error (in Degrees) as a Function of Imagined Heading in Experiments 1 and 2

	Imagined heading							
Experiment	0°	45°	90°	135°	180°	225°	270°	315°
Experiment 1								
M	17.49	21.04	24.01	22.93	22.25	25.60	20.19	22.02
SD	5.44	5.78	7.33	8.31	6.24	7.63	5.22	7.95
Experiment 2								
M	24.85	33.88	37.37	31.05	33.50	27.90	30.41	22.34
SD	9.27	17.23	22.00	17.41	15.06	16.53	15.24	4.54

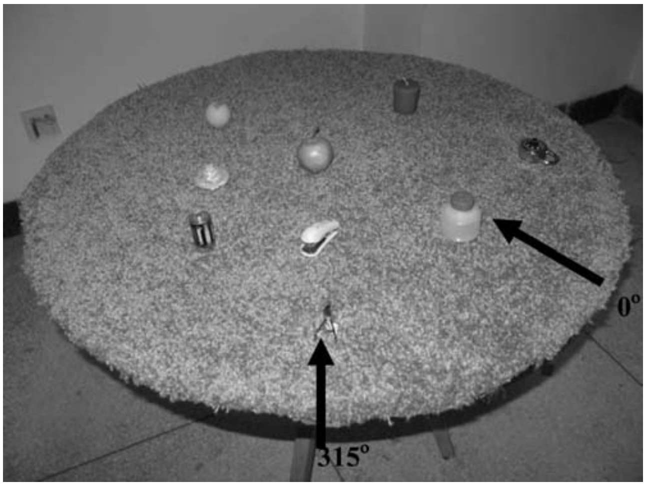

Figure 5. Layout of objects used in Experiment 2.

Materials, Design, and Procedure

The materials were similar to those used in Experiment 1, except that two objects (a stapler and a hat) were added in the layout, as illustrated in Figure 5. The design was identical to that in Experiment 1. The test trials for judgments of relative directions were identical to those used in Experiment 1. In other words, the two new added objects were never involved in the test trials. The procedure was similar to that in Experiment 1, except that participants learned two more objects in the learning phase.

Results

Interobject Eye Movements

An example of a participant's eye movements during learning is illustrated in Figure 6. Fixations were defined as in Experiment 1. The total frequencies of interobject eye movement in the five 30-s viewing periods of the five learning–pointing sessions for each interobject eye movement category and each participant are presented in Table 3. There are 72 possible eye movements for the layout used in this experiment (9×8): 24 for aligned-0°, 28 for aligned-315°, and 20 for others. Hence, the a priori proportion of the aligned-315° category in the categories of aligned-315° and other is 58%, 28/(28 + 20), and in the categories of aligned-315° and aligned-0° is 53%, 28/(28 + 24). Binomial tests including the category of aligned-315° and the category of other showed that for all participants, the observed proportion of interobject eye movement in the category of aligned-315° was significantly higher than 58%, $\chi^2(1) \geq 85.82$. Binomial tests including the category of aligned-315° and aligned-0° showed that for 7 of the 8 participants (except for Participant 5 in Table 3), the observed proportion of interobject eye movements in the category of aligned-315° was significantly higher than 53%, $\chi^2(1) \geq 16.84$. Although for Participant 5 the observed proportion of the category of aligned-315° was 60% and numerically higher than 53%, it was not significantly different from 53%, $\chi^2(1) = 3.22$.

The percentages of interobject eye movements along all directions (0° to 315° in 45° steps and others) for each participant were also calculated. Mean percentage of interobject eye movements and a priori percentage are plotted in Figure 7 as a function of direction. As illustrated in Figure 7, the observed percentage along the directions of aligned-315° was higher than predicted by the a priori percentages, whereas the observed percentage along the directions of aligned-0° was not higher or lower than predicted by the a priori percentages. The observed percentage along the other directions was much lower than predicted by the a priori percentage.

The difference between the observed percentage of eye movements and the a priori percentage of eye movements was analyzed in repeated measure ANOVAs with terms for direction (0° to 315° in 45° steps). The effect of direction was significant, $F(7, 49) = 18.48$, $p < .001$, $MSE = 0.002$. The percentage difference at the directions of aligned-315° was significantly larger than that at the directions of aligned-0°, $t(49) = 8.36$. More specifically, the planned comparisons showed that the percentage difference at directions parallel to the viewing direction (315° and 135°) was significantly larger than that at the directions of aligned-0°, $t(49) = 11.24$. The percentage difference at the directions orthogonal with the viewing direction (45° and 225°) was significantly bigger than that at the directions of aligned-0°, $t(49) = 2.40$.

Judgments of Relative Direction

Pointing latency was analyzed in repeated measure ANOVAs with terms for imagined heading (0° to 315° in 45° steps). Mean pointing latency is plotted in Figure 8 as a function of imagined heading. As illustrated in Figure 8, there were two major findings. First, participants were quicker at pointing to objects from the imagined heading of 315°, which corresponded to the viewing direction, than from the heading of 0°. Second, participants were quicker at pointing to objects from the novel imagined headings of 45°, 135°, and 225°, which were aligned with the viewing direction, than from the novel imagined headings of 0°, 90°, 180°, and 270°, which were misaligned with the viewing direction.

All of these conclusions were supported by statistical analyses. The effect of imagined heading was significant, $F(7, 49) = 10.61$,

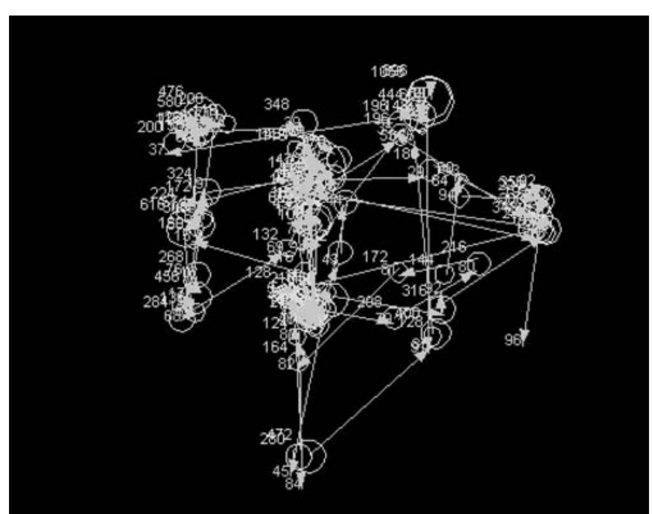

Figure 6. An example of eye movement during learning the layout in Experiment 2.

Table 3
The a Priori Frequency of Interobject Directions and the Observed Frequencies of Interobject Eye Movement Along the Aligned-0° Axes the Aligned-315° Axes, and the Other Axes in Experiment 2

Axes	A priori frequency	Observed frequency of each participant (P)							
		P1	P2	P3	P4	P5	P6	P7	P8
Aligned-0°	24	57	93	67	67	90	83	34	72
Aligned-315°	28	163	182	280	276	134	207	102	157
Other	20	8	19	13	13	9	11	3	12
χ^2		36.28**	16.84**	100.60**	97.80**	3.22	35.87**	24.49**	19.95**

Note. Chi-square values were calculated from a binomial test comparing the observed frequencies of interobject eye movement along the aligned-0° axes and the aligned-315° axes under a binomial distribution with a probability parameter determined by the priori frequencies. Aligned-0° axes = directions 0°, 90°, 180°, and 270°; aligned-315° axes = directions 45°, 135°, 225°, and 315°; other axes = all other directions.
** $p < .01$. * $p < .05$.

$p < .001$, $MSE = 0.26$. The planned comparisons showed that latency at the heading of 315° was significantly different from latencies at all other headings, $t(49) \geq 3.05$. The planned comparison of the novel headings 45°, 135°, and 225°, which were aligned with the viewing direction of 315°, to the novel headings of 0°, 90°, 180°, and 270°, which were misaligned with the viewing direction of 315°, was significant, $t(49) = 4.03$.

Mean angular error is presented in Table 2 as a function of imagined heading. Two of the 8 participants pointed quite accurately, with angular error less than 25° for all imagined headings. The Pearson correlation r between mean latency and mean angular error across headings was .78, which was significant, $p < .05$.

Discussion

The results of interobject eye movements showed that all participants moved their eyes to fixate on the next object more frequently along the directions aligned with their viewing direction than along the directions misaligned with their viewing direction. This preference of the viewing direction was statistically significant for 7 of the 8 participants. Results for judgments of relative direction showed that retrieval of spatial memories from headings aligned with the viewing direction was quicker too. No evidence suggested that participants preferred the directions aligned with the intrinsic axis of 0°–180° when it was not the symmetric axis. These results confirmed the conclusion in Experiment 1 that people are able to encode in and retrieve from spatial memory the structure of a layout in terms of a spatial frame of reference that is solely determined by the layout geometry (e.g., symmetry) supporting the intrinsic model of spatial memory proposed by Mou and McNamara (2002). The finding that participants preferred the spatial frame of reference aligned with the viewing direction in both encoding and retrieval is consistent with the proposal that the viewing direction is one of the important cues determining the intrinsic reference directions (Mou & McNamara, 2002). Of importance, the similar patterns in eye movements and judgments of relative direction confirmed that encoding and retrieval of spatial memory are processed in terms of the same intrinsic frame of reference.

General Discussion

The goal of this project was to investigate whether the spatial reference direction that is used to mentally represent the spatial

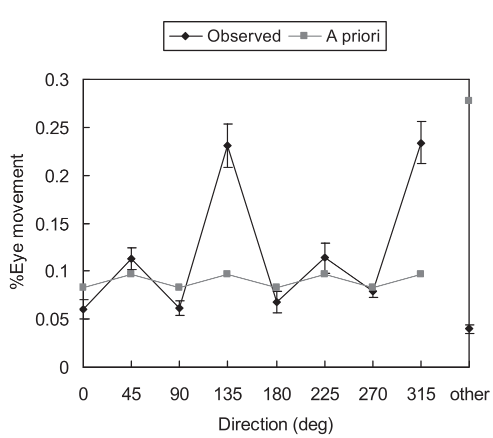

Figure 7. Observed percentage and a priori percentage of interobject eye movements as a function of direction in Experiment 2. Error bars are confidence intervals corresponding to ±1 *SE*, as estimated from the analysis of variance.

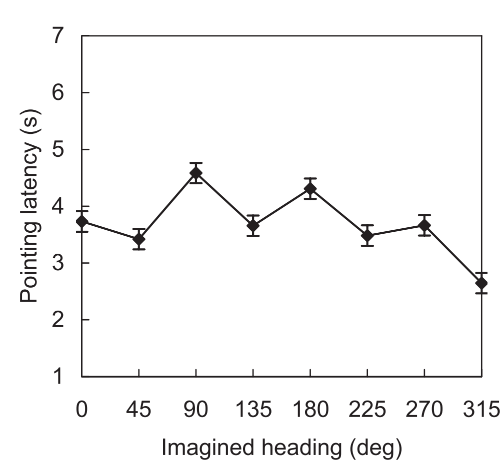

Figure 8. Pointing latency as a function of imagined heading in Experiment 2. Error bars are confidence intervals corresponding to ±1 *SE*, as estimated from the analysis of variance.

structure of a layout can be established solely with the influence of the layout geometry. The results clearly indicated that participants established spatial reference directions that were determined by the layout geometry rather than by the viewing direction. Experiment 1 showed that when participants viewed a layout with a symmetric axis and the direction of the symmetric axis was different from the viewing direction, all participants moved their eyes from the fixation on one object to the next fixation on a different object more frequently along the directions aligned with the symmetric axis than along the directions aligned with the viewing direction. In most of the participants (6 out of 8), this preference for the directions aligned with the symmetric axis was statistically reliable. When participants used memory to make judgments of relative direction, they were consistently quicker at the imagined headings aligned with the symmetric axis than at the imagined headings aligned with the viewing direction.

The preference for the directions aligned with the symmetric axis cannot be attributed to factors other than the layout geometry. The environmental influence was well controlled by making both the direction of the symmetric axis and the viewing direction 22.5° misaligned with the walls of the room, removing the possible confounding effect of environmental influence (e.g., Shelton & McNamara, 2001). Participants were never instructed to use any particular order of objects to learn the locations of the objects, thus removing the possible confounding effect of instruction (e.g., Mou & McNamara, 2002). Furthermore, Experiment 2 showed that when we added two objects to remove the symmetric axis in Experiment 1, the preferred directions in both eye movements and judgments of relative direction were altered to be aligned with the viewing direction. Hence, this project demonstrated that the spatial reference directions that are used to represent the locations of a collection of objects in memory can be solely determined by the intrinsic geometry of the spatial layout of those objects.

These results strongly support the key claim of the intrinsic model of spatial memory, proposed by Mou and McNamara (e.g., Mou & McNamara, 2002; Mou, Zhao, & McNamara, 2007), which is that people establish intrinsic reference directions to represent locations of objects in memory. An important next step in developing this model is to specify in greater detail the nature of these spatial representations and the role of eye movements in building them. One possibility is that eye movements reflect the encoding of interobject spatial relations and that interobject spatial relations are encoded with higher probability or greater fidelity in directions aligned with the intrinsic reference directions than in other directions (e.g., Rump & McNamara, 2006). It is also possible that the sequence of eye fixations establishes the spatial reference directions. This possibility could be tested by testing spatial memory after people learn the layout of objects presented in a sequential order that is different from the viewing direction. If the sequence of eye fixations establishes the spatial reference directions, performance should be better for the imagined heading parallel to the order of presenting the objects. Research in our laboratory is investigating these issues.

These results are difficult to explain in other contemporary theories of spatial memory. Wang and Spelke (2002) proposed that there are three systems of spatial memory. In the egocentric system, people represent locations of objects with respect to themselves. In the allocentric system, people represent the shape of the environment (e.g., the shape of a surrounding room); however, this system does not accommodate locations of objects. In the viewpoint-dependent system, people store enduring viewer-centered representations (e.g., visual–spatial "snapshots") of landmarks and scenes for visual recognition (e.g., Diwadkar & McNamara, 1997). As we understand Wang and Spelke's model, both egocentric spatial representations and viewer-centered snapshot representations predict that judgments of relative direction should be better at the imagined heading parallel to the viewing direction regardless of the layout geometry. Furthermore, both egocentric spatial representations and viewer-centered snapshot representations predict that the directions aligned with the viewing direction should be preferred regardless of the layout geometry. Because the allocentric system in their theory does not represent the locations of objects, it also cannot explain the results that the preferred directions in eye movements and judgments of relative direction were determined by the symmetric axis of the layout.

The theory proposed by Sholl and her colleagues (Easton & Sholl, 1995; Sholl, 2001; Sholl & Nolin, 1997) includes an allocentric system accommodating interobject spatial relations. This allocentric system is orientation free itself, but when people interact with the environment, their egocentric front will be set as the orientation of the allocentric system. This theory is consistent with the observation that participants moved their eyes in a systematic way when encoding interobject spatial relations. Also, this theory can explain the finding that participants preferred the viewing direction in Experiment 2 of this project as the direction of the allocentric system may be fixed by the egocentric front. However, it is still challenging for this theory to explain why participants preferred directions different from the viewing direction and why layout geometry mattered.

This project also showed that the preferred directions in interobject eye movements and judgments of reference direction were parallel to the viewing direction when there was no symmetric axis in the layout in Experiment 2. This learning orientation dependency does not necessarily imply that people established egocentric reference directions to specify objects' locations when there was no symmetric axis in the layout. Mou, McNamara, Valiquette, and Rump (2004) showed that learning orientation dependency of judgments of relative direction was caused by an intrinsic frame direction that was defined parallel to the learning direction. They found that learning orientation dependency in judgments of relative direction was observed even when participants physically moved to align their actual heading with the imagined headings in the testing trials that were presented after their movement. This result indicated that the spatial reference directions were not fixed with the egocentric front when participants locomoted between learning and testing. Hence, the spatial reference directions, which caused the learning orientation dependency in pointing, were allocentric rather than egocentric.

Although this project demonstrated that people represent locations of objects with respect to an intrinsic frame of reference in a layout with objects lined up column by column and row by row, it is still an open question how people represent locations of objects in a layout without clear intrinsic structures. One possibility is that people may establish an intrinsic reference direction that is parallel to their viewing direction and may represent interobject spatial relations with respect to the intrinsic reference direction. The other possibility is that no intrinsic reference directions are established to represent objects' locations. The other open question is the amount of time needed to establish intrinsic reference directions. In this study, the layout of the objects was well studied for a relatively long time. It is possible that no intrinsic reference directions are established if the learning time is sufficiently brief. Research in our laboratory is investigating these issues.

Past research may provide evidence on the relative salience of instructions, layout geometry, viewing direction, and surrounding environmental structures as cues to the selection of intrinsic reference directions. Mou and McNamara (2002, Experiment 2) showed that the preferred direction in judgments of relative direction was determined by the direction in which participants were instructed to remember the locations of the objects, even when the instructed direction was different from the symmetric axis of the layout. This finding indicates that instruction is a stronger cue than the symmetric axis of a layout. This project (Experiment 1) showed that the preferred direction in judgments of relative direction was determined by the symmetric axis of the layout instead of the viewing direction. This finding indicates that the symmetric axis of a layout is a stronger cue than the viewing direction of an observer. This relation may depend, however, on the angular distance between the viewing direction and the symmetric axis. For instance, a symmetric axis perpendicular to the viewing direction might not be as salient as one at a small acute angle from it. Finally, Shelton and McNamara (2001, Experiment 2) showed that when participants learned a layout from a single viewpoint, the preferred direction in judgments of relative direction was parallel to the viewing direction even when the viewing direction was misaligned with the external environmental structures. In summary, available evidence suggests that these cues might be ordered as follows in salience or strength: instructions, layout geometry, viewing direction, and surrounding environmental structures. This ordering, however, almost certainly depends on aspects of the learning situation that have not been investigated (e.g., distance between the layout and surrounding environmental structures) and on interactions between the cues themselves.

The other important result of this project was that the preferred directions of interobject eye movements were very consistent with the preferred directions in judgments of relative direction. All participants moved their eyes to fixate on the next object more frequently along the preferred directions in judgments of relative direction. This result indicates that the same spatial reference directions are used in encoding and retrieval of spatial memory and provides independent evidence that the patterns of performance observed in judgments of relative direction in previous studies reflect which spatial reference directions participants used in representing spatial relations in memory. We acknowledge that because this is the first time in the literature of spatial memory that eye movements have been used to determine which reference directions people use to represent locations of objects, more evidence may be needed to confirm the conjecture that interobject eye movements during encoding can be used to infer the nature of spatial memory independently. Also, it will be interesting to see whether there are systematic interobject eye movements during recognition of the spatial relations of a layout and whether the interobject eye movements during scene recognition are consistent with the interobject eye movements during spatial learning.

Our claim is that people retrieve the locations of objects from representations based on intrinsic reference systems established at encoding. We acknowledge that people must be able to compute objects' locations relative to their egocentric reference systems in action. For example, the allocentric spatial representation must be translated into egocentric coordinates by aligning the egocentric front with the imagined facing direction when participants point to the target object. In the introductory section, we claimed that encoding develops and refines spatial memory, whereas retrieval uses it. We do not exclude the possibility that spatial memory can be developed with the retrieval process. For example, some interobject spatial relations that are not encoded during learning might be developed in memory during retrieval. However, we do not believe the spatial reference directions in memory can be altered during retrieval because the orientation-dependent spatial judgments have been reported in a large body of studies (McNamara, 2003, for a review).

In conclusion, the present findings indicate that an intrinsic frame of reference used to specify objects' locations in memory can be solely determined by the intrinsic geometry of a layout of objects. Viewing direction is also an important cue in the selection of intrinsic reference directions, but its effectiveness seems to depend on the other cues available. People move their eyes along the intrinsic reference directions when encoding interobject spatial relations, and retrieval of spatial relations in directions consistent with the same intrinsic reference directions is relatively efficient.

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